

GEORGIA INSTITUTE OF TECHNOLOGY

OFFICE OF CONTRACT ADMINISTRATION

PROJECT ADMINISTRATION DATA SHEET

GEORGIA TECH LIBRARY

☒

ORIGINAL

☐

REVISION NO.

Project No. E-25-695

GTRI/STP

DATE 7/12

Project Director: Dr. Ward O. Winer

School/~~inst~~ ME

Sponsor: National Science Foundation

Type Agreement: Grant No. MEA-8320502

Award Period: From 7/1/84 To 12/31/85 * (Performance) 3/31/86 (Reports)

Sponsor Amount:

This Change

Total to Date

Estimated: \$ \$ 134,933

Funded: \$ \$ 134,933

Cost Sharing Amount: \$ 12,326

Cost Sharing No: E-25-322

Title: "Thermal Phenomena in Tribology"

ADMINISTRATIVE DATA

OCA Contact Lynn Boyd x4820

1) Sponsor Technical Contact:

2) Sponsor Admin/Contractual Matters:

Elbert L. Marsh

Sharon Graham

Program Manager, Mechanical Systems

Grants Official

Division of Mechanical Engr. & Applied

National Science Foundation

Mechanics; National Science Foundation

Washington, DC 20550

Washington, DC 20550

(202) 357-7386

(202) 357-9626

Defense Priority Rating: n/a

Military Security Classification: n/a

(or) Company/Industrial Proprietary: n/a

RESTRICTIONS

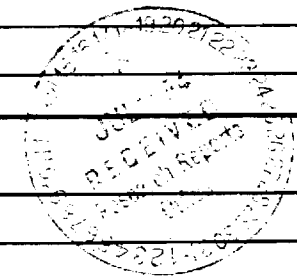
See Attached NSF Supplemental Information Sheet for Additional Requirements.

Travel: Foreign travel must have prior approval – Contact OCA in each case. Domestic travel requires sponsor approval where total will exceed greater of \$500 or 125% of approved proposal budget category.

Equipment: Title vests with GIT.

COMMENTS:

*Includes usual 6 month unfunded flexibility period.



COPIES TO:

Sponsor I.D. #02.107.000.84.021

Project Director
Research Administrative Network
Research Property Management
Accounting

Procurement/EES Supply Services
Research Security Services
Reports Coordinator (OCA)
Research Communications (2)

GTRI
Library
Project File
Other Newton

12 / 88

GEORGIA TECH LIBRARY

GEORGIA INSTITUTE OF TECHNOLOGY
OFFICE OF CONTRACT ADMINISTRATION

NOTICE OF PROJECT CLOSEOUT

Date 1/26/89

Project No. E-25-695

Center No. F5787-OA0

Project Director W.O. Winer

School/Lab ME

Sponsor National Science Foundation

Contract/Grant No. MEA-8320502

GTRC XX GIT

Prime Contract No. N/A

Title Thermal Phenomena in Tribology

Effective Completion Date 6/30/88 (Performance) 9/30/88 (Reports)

Closeout Actions Required:

- None
X Final Invoice or Copy of Last Invoice
 Final Report of Inventions and/or Subcontracts - Already Received
X Government Property Inventory & Related Certificate
 Classified Material Certificate
X Release and Assignment
 Other

Includes Subproject No(s).

Subproject Under Main Project No.

Continues Project No. Continued by Project No.

Distribution:

- X Project Director
X Administrative Network
X Accounting
X Procurement/GTRI Supply Services
X Research Property Management
 Research Security Services

- X GTRC
X Project File
X Contract Support Division (OCA) (2)
 Other

Renewal Application
for
Continuing Grant
MEA-8320502
Ward O. Winer, Principal Investigator

I. Introduction

This renewal application is for the second year of NSF Grant No. 8320502 entitled "Thermal Phenomena in Tribology". The Award letter dated June 26, 1984 stated the award was a continuing award approved on scientific merit for three years subject to scientific progress and availability of funds. This document presents a summary of scientific progress to date and the budget request for the second year.

II. Summary of Scientific Progress

Significant scientific progress has occurred during the first 10 1/2 months of this grant (July 1, 1984 to mid-May 1985 when this report was prepared). The timing of grant initiation made it possible to partially support a Ph.D. student who was well into his research. Therefore the time supported was very productive. This was fortunate because the two major pieces of capital equipment included in the first year grant were not functional until well into the grant period. The IR scanning system with microscopic optics was not complete until the end of January 1985. The computer mass storage system for storing video IR images has only recently become operative having had to be returned to the manufacturer once. Both systems are operational now as is a real-time video frame analyzer which became available through a DOD-URIG. This system will play an important role in the progress over the remaining period of the grant.

IIa. Analysis of Surface Temperatures in Tribo-elements

Two papers have been completed and submitted for publication concerning the surface temperatures in sliding tribo-contacts [1,2]. These papers were extensions of the Ph.D. Thesis research of Burak Gecim [3]. The subject of these studies was the effect of system variables on the surface temperature. The system variables studied included the presence of thin layers [1] and gross geometry [2]. These represent common variations in rotating tribo-elements.

The layer study [1] consisted of the solution to the steady heat conduction problem of a rotating layered cylinder. The governing differential equations (for the film and the substrate) were solved by using an integral transform technique. The presence of a surface film the thickness of which is measured in micrometers can substantially change the level of the surface temperature. The effect of the surface film on the surface temperature depends on: respective thermal properties of the film and the substrate; relative surface speed; heat source (contact) size; and surface film thickness. The extent of the effect of the film on the surface temperature is limited to a range of these parameters. Outside this range (i.e., thin film/low speed or thick film/high speed) the surface temperature rise is determined by the thermal properties of the substrate, or by the properties of

the film alone, respectively. Hence, outside this range, a further change in the film thickness does not influence the surface temperature rise. Dimensionless plots showing the change in surface temperature rise as a function of material thermal properties, surface speed, heat source size, and film thickness are presented. Behavior for specific material combinations are also presented.

In the second paper [2], the three cases presented are variations in the geometry and the thermal boundary conditions pertinent to the classical flash temperature theory. First, the case of multiple surface heat sources is presented. The relative location of the sources is the critical factor in predicting the local temperatures at each contact. Second, the case of a short cylinder (or a disk) is analyzed. In addition to the lateral surface boundary conditions, convective cooling from the side faces is considered. A considerable reduction in bulk temperature can be achieved by effective cooling from the side faces. Third, the case of a hollow cylinder is studied where, in addition to the outer boundary conditions, uniform internal heating (or cooling) is considered. The bulk temperature can be varied significantly by changing the magnitude (and direction) of the internal heat flux.

A third analytical effort was started and will be continued. That is the stochastic modelling of the surface temperatures at the real areas of contact in unlubricated sliding contacts. This model builds on the transient asperity temperature analysis [3,4]. The location and size of the real areas of contact are generated randomly within specified limits and the transient temperature at the spot is determined by the published analysis [4]. The specified limits are that the spot must be within the apparent area of contact, must have a diameter within a range consistent with experimental observation, and the total area of spots must be equal to the applied load divided by the material hardness. A given spot will remain as an active load support as long as the maximum surface temperature is less than some fraction of the melting point of the material in degrees Kelvin. The last requirement is based on the assumption that as the surface temperature increases, as a result of frictional heating, it will reach a value where the material will flow under the applied stress. Once the flow begins the load is shifted to a new location. This model qualitatively fits some of the observations of surface temperature dynamics as viewed in infrared video recordings. If this analysis can adequately model surface temperature dynamics, one may be able to manipulate the model to determine the engineering parameters (such as surface geometry and material properties) which control the transition between mild and severe wear. This modelling will continue in the second year of the program.

IIb. Experimental Observations of Surface Temperatures

Observations of surface temperatures have proceeded along three distinct paths, two of which have already lead to the submission of publications [5,6 and 7]. These first two were concerned with hard bodies sliding against hard bodies. The third effort is concerned with the surface temperatures of compliant polymers sliding against a hard surface and is part of the cooperative program with BAM in West Berlin.

The surface temperature observations for hard surfaces have progressed from photographic color-temperature studies of steels sliding against sapphire

[5,6] in a pin-on-disk device to infrared scanning measurements of the surface temperature of an automotive cam loaded against a flat lifter [7]. The pin-on-disk experiment was nominally steady (e.g., applied load and sliding speed) yet the real area of contact was very dynamic. By varying the film exposure time when photographing the hot spots at the sliding interface, the instantaneous number of real areas of contact could be estimated and was found to be about seven. The results of this work are an important adjunct to the oxidational wear modelling work of T. F. J. Quinn [6].

The automotive cam and lifter work was part of the thesis research of Jan Griffioen [8]. He was able to take advantage of a sophisticated cam and lifter simulator built in this laboratory under a contract with General Motors Research to study cam and lifter tribology. The research conducted under the NSF grant was to develop the IR optics, data retrieval and analysis systems to measure the infrared radiation from the cam surface at peak lift for cam speeds up to 1500 rpm. The scanner used was the AGA unit on loan from the Architecture School which the student had started to work with before this grant began. For bulk oil temperatures of 100°C peak lift cam temperatures were in excess of 300°C which has significant implications with respect to lubricant oxidation, lubricant surface reactions and surface layer formations.

The third area of surface temperature measurement is that of a polymer (PTFE) sliding against CaF_2 . The program is in cooperation with H. Czichos at BAM in West Berlin. The West German group has conducted an extensive study of the tribological behavior of polymers sliding against glass [9]. The conditions used are a sliding speed of 17 mm/s and a load of 20 N on a 3 mm diameter pin. They [9] have shown that after several hundred meters of sliding the wear rate increases several fold and the wear mechanism changes. Visual observations were made by video recording the wear surface with a microscope viewing through the glass surface. Because of a known transition temperature of PTFE near room temperature, it is thought that the transition in wear may be thermally induced. Our part of the program is to attempt to measure the surface temperatures of the PTFE during sliding. To date we have duplicated the BAM friction and wear measurements including the observation of the wear transitions and wear morphology on video tape for glass and sapphire countersurfaces. IR video recordings have been made with the sapphire counterface. The change in character of the surface associated with the wear transition was observed. However, because of the low temperatures and limited IR transmission of the sapphire the signal-to-noise ratio is low. The CaF_2 single crystal was chosen for its high IR transmission and because the temperature rise anticipated is only a few degrees Celsius. At the time of this writing the IR video tapes have been obtained and the wear transition observed in the IR image, but the temperatures have yet to be quantified. This research will also be continued in the second year of this program.

In summary several exciting advances have been made during the first year. The capital equipment made available will be in full operation by the end of the first year which will be of great advantage in subsequent years of the program.

II. Funds Estimated to be Remaining at End of One Year

This request is for the second year funding to begin in mid-September. It is estimated that the funds remaining will be less than \$500.

Bibliography

1. Gecim, B., and Winer, W. O., "Effect of a Surface Film on the Surface Temperatures of a Rotating Cylinder," (accepted for publication in **Trans. ASME, Journal of Tribology**).
2. Gecim, B., and Winer, W. O., "Steady Temperatures in a Rotating Cylinder: Some Variations in the Geometry and the Thermal Boundary Condition," (submitted for publication in **Trans. ASME, Journal of Tribology**).
3. Gecim, B., **Temperature Prediction in Mechanical Components, An Analytical Approach**, Ph.D. Dissertation, Georgia Institute of Technology (March 1984).
4. Gecim, B., and Winer, W. O., "Transient Temperatures in the Vicinity of an Asperity Contact," ASME Paper No. 84-Trib-15 (to be published in **Trans. ASME, Journal of Tribology**).
5. Quinn, T. F. J., and Winer, W. O., "The Thermal Aspects of Oxidational Wear," **Wear, Vol. 102**, (1985) 67-80.
6. Quinn, T. F. J., and Winer, W. O., "An Experimental Study of the "Hot-Spots" occurring during the Oxidational Wear of Tool Steel on Sapphire," (submitted to **Trans. ASME, Journal of Tribology** for publication).
7. Bair, S., Griffioen, J., and Winer, W. O., "The Tribological Behavior of an Automotive Cam and Flat Lifter System," (submitted to **Trans. ASME, Journal of Tribology** and the ASME/ASLE Tribology Conference 1985).
8. Griffioen, J., "Temperature Measurements in Tribo-Contacts by Means of Infrared Radiometry," Ph.D. Thesis, School of Mechanical Engineering, Georgia Institute of Technology, Atlanta, Georgia (May 1985).
- 9a. Czichos, H., "In-situ Investigation of Tribological Processes on Sliding Polymer Interfaces," **Proceedings 3rd International Solid Lubricants Conferences**, ASLE Publishers (1984).
- 9b. Czichos, H., "Contact Deformation and Static Friction of Polymers -- on Influences of Viscoelasticity and Adhesion," **International Symposium on Polymer Wear and its Control**, St. Louis, Missouri (April 1984).

Current and Pending Research Support

Ward O. Winer
Principal Investigator

[all research performed at Georgia Institute of Technology]

IA. Current Support (in addition to current support on this grant at 4 man-months per year)

- a. General Motors, Rochester Products Division
"The Tribological Behavior of an Automotive Cam and Roller Lifter System"
\$55,000
February 1985 to January 1986
1 month
- b. The Torrington Company
"Investigation of Roller Follower Skidding Phase II"
\$50,759
April 1985 to January 1986
1 month
- c. Martin Marietta Company - DOE - ORNL
"Development of a Theory of Wear of Ceramics"
\$257,769
March 1983 to March 1987
5 months
- d. NSF
"Development of a Recommendation to the National Science Foundation on Long Range Goals and Priorities for Research in Thermal Systems"
\$40,000
January 1984 to July 1985
This work is being conducted through ASME with W. O. Winer as Principal Investigator. No funds are included for salaries. The report is in final stages of completion and is expected to be finished by the time this renewal begins (October 1).

IB. Proposals Pending

- a. NSF (this renewal proposal)
"Thermal Phenomena in Tribology"
\$299,966
July 1, 1984 to December 31, 1987
4 man months per year (or 33% time)
- b. No other formal research commitments have been made nor proposals submitted at this time. However, consideration is being given to participating in an NSF ERC proposal and a DOD SDI proposal with others.

II. S. Bair, Senior Research Engineer (research faculty associate on this proposal)

A. Current Support

- a. General Motors Rochester Products Division (as IAa above)
4 months
- b. Torrington (as IAb above)
5 months
- c. Martin Marietta - DOE - ORNL (as IAc above)
12 months

B. Pending

- a. NSF (this proposal IBa above)
- b. (as per IBb above)

III. n/a

IV. This proposal is not being submitted to any other agency.

APPENDIX III

SUMMARY
PROPOSAL BUDGET

2nd year

ORGANIZATION		PROPOSAL NO.		DURATION (MONTHS)	
				Proposed	Granted
GEORGIA TECH RESEARCH CORPORATION		AWARD NO.			
PRINCIPAL INVESTIGATOR/PROJECT DIRECTOR					
Ward O. Winer					
1. SENIOR PERSONNEL: PI/PD, Co-PI's, Faculty and Other Senior Associates (List each separately with title; A.6. show number in brackets)		NSF FUNDED PERSON-MOS.		FUNDS REQUESTED BY PROPOSER	FUNDS GRANTED BY NSF (IF DIFFERENT)
		CAL.	ACAD.	SUMR	
W. O. Winer, Professor		4			\$ 26,700
S. Bair, Research Engineer		2			5,500
() OTHERS (LIST INDIVIDUALLY ON BUDGET EXPLANATION PAGE)					
(2) TOTAL SENIOR PERSONNEL (1-5)		6			32,200
2. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS)					
() POST DOCTORAL ASSOCIATES					
() OTHER PROFESSIONALS (TECHNICIAN, PROGRAMMER, ETC.)					
(1) GRADUATE STUDENTS 1/3 time					10,000
(1) UNDERGRADUATE STUDENTS 250 hours per year					1,500
(1) SECRETARIAL-CLERICAL 10% time					2,000
(-) OTHER					
TOTAL SALARIES AND WAGES (A+B)					45,700
FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS) 21.2% of A + B5					7,250
TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A+B+C)					52,950
3. PERMANENT EQUIPMENT (LIST ITEM AND DOLLAR AMOUNT FOR EACH ITEM EXCEEDING \$1,000; EQUIPMENT OVER \$5,000 REQUIRE CERTIFICATION)					
TOTAL PERMANENT EQUIPMENT					
TRAVEL 1. DOMESTIC (INCL. CANADA AND U.S. POSSESSIONS)					1,000
2. FOREIGN West Germany					2,743
see attached explanation					
PARTICIPANT SUPPORT COSTS					
1. STIPENDS \$					
2. TRAVEL					
3. SUBSISTENCE					
4. OTHER					
TOTAL PARTICIPANT COSTS					
OTHER DIRECT COSTS					
1. MATERIALS AND SUPPLIES					1,500
2. PUBLICATION COSTS/PAGE CHARGES					400
3. CONSULTANT SERVICES					
4. COMPUTER (ADPE) SERVICES					
5. SUBCONTRACTS					
6. OTHER					
TOTAL OTHER DIRECT COSTS					1,900
TOTAL DIRECT COSTS (A THROUGH G)					58,593
INDIRECT COSTS (SPECIFY) 64.2% of Total Direct Cost less Capital Equipment Cost (proposed rate for the period 7/1/85 - 6/30/86 & subject to change thereafter)					37,617
TOTAL INDIRECT COSTS					37,617
TOTAL DIRECT AND INDIRECT COSTS (H + I)					96,210
RESIDUAL FUNDS (IF FOR FURTHER SUPPORT OF CURRENT PROJECTS GPM 252 AND 253)					
AMOUNT OF THIS REQUEST (J) OR (J MINUS K)					\$ 96,210
I/PI TYPE NAME & SIGNATURE		DATE		FOR NSF USE ONLY	
Ward O. Winer		5/23/85		INDIRECT COST RATE VERIFICATION	
JST. REP. TYPED NAME & SIGNATURE		DATE		Date Checked	Date of Rate Sheet
Lynn Boyd		5/23/85			Initials - OGC
					Program

Foreign Travel Budget

1st year

Three weeks		
travel	1,000	
21 days of per diem	1,743	
at \$83 per day	<u>2,743</u>	2,743

2nd year

Three weeks		
travel	1,000	
21 days of per diem	1,743	
at \$83 per day	<u>2,743</u>	2,743

3rd year

Three weeks		
(beginning of third year)		
travel	1,000	
21 days of per diem	1,743	
at \$83 per day	<u>2,743</u>	2,743

Two weeks		
(end of contract for report completion)		
travel	1,000	
14 days of per diem	<u>1,162</u>	2,162
	2,162	

TOTAL:		\$10,391
--------	--	----------

Renewal Application
for
Continuing Grant
MEA-8320502
Ward O. Winer, Principal Investigator

I. Introduction

This renewal application is for the third year of NSF Grant No. 8320502 entitled "Thermal Phenomena in Tribology". The Award letter dated June 26, 1984 stated the award was a continuing award approved on scientific merit for three years subject to scientific progress and availability of funds. This document presents a summary of scientific progress during the second year and the budget request for the third year.

II. Summary of Scientific Progress

Significant progress was made during the first year of the grant (7/84 to 6/85) because the grant started at a time when two PhD students were well into their research. As reported in the progress report last year there were several publications accepted for publication during the first year. The progress during the second year has been both in the starting of new projects and continuing existing projects with new students. Although exciting progress has been made, less work has reached the publication stage. The experimental studies of the surface temperature dynamics during sliding have been continued along two distinct lines as discussed below. The stochastic computer modelling of the surface temperatures to predict wear as mentioned in the last progress report has not progressed because of the unavailability of an interested and qualified student. The projects currently underway are expected to yield publishable results during the coming year.

IIa. Experimental Studies of Surface Temperatures in Dry Sliding.

These studies have been on either hard surfaces or soft polymeric surfaces in unlubricated sliding contacts. Quite different surface temperature dynamics are observed in these two cases. For the hard surfaces the surface temperatures fluctuate very rapidly under nominally steady sliding conditions. The instantaneous temperatures can be quite high. For the softer polymeric surfaces the surface temperatures are much lower and fluctuations are not observed.

In the case of hard sliding surfaces several methods of observation have been employed to gain insight into the behavior of the high temperature regions on the surface during sliding. Single line IR observations show that some of the hotspots last less than 400 microseconds while others can persist for up to 200 milliseconds as seen in the field scan mode. Therefore the fixed scanning rate of the infrared system is unable to definitively determine how many spots exist simultaneously. Also, in the case of the hard surfaces, many of the hotspots could be seen with the naked eye and have been photographed with ordinary film. Therefore an attempt was made to record the hotspot dynamics simultaneously with high speed motion picture (to 500 frames/second) and with a standard video camera using a beam splitter between the contact and the cameras. The motion picture results were only of limited value because the

hotspots gave limited light intensity for the film exposure. The video tapes were analyzed with a video frame analyzer. Because of the nature of the detector in each of these cases only those spots whose temperature is greater than about 1000 C will be observed.

The video analysis of the hotspots occurring on the surface of a steel pin in dry sliding against a sapphire disk resulted in several interesting observations. Using computer coupled video frame analysis statistics of spot size, number, total spot area, duration, and spot movement could be obtained. The details of these studies will not be presented here but will appear in future publications. Typical results show that the average spot size is between 50 and 80 micrometers in diameter and the spot may persist for up to 200 milliseconds or more in some cases. As a rule larger spots persist for longer periods. The average number of hotspots per frame appears to increase with load while the average diameter does not although these trends are not well confirmed at this time. The ratio of hotspot area to apparent area ranged from a high of 0.01 to 0.0001. In the limited attempt undertaken to relate the hotspot area to the load and the material hardness no obvious relationship was found except that the load divided by the hardness may be an upper limit on the hotspot area as might be expected. One final interesting observation was that in a few cases the hotspot persisted for several seconds and its position could be followed with the video analyzer. In one case the hotspot persisted for three seconds and moved in the direction of sliding at an average velocity of about 100 micrometers per second before it disappeared. The surface sliding velocity was 2 meters per second.

To date we have found the reproducibility of the hotspots to be difficult. The study will continue to try to determine the cause of the hotspot formation and the relationship of them to the operating conditions of the tribosystem.

The infrared surface temperature measurements of the sliding polymeric surfaces introduced in last year's report have been continued. This work is in cooperation with the people at BAM in Berlin who have done extensive research on the friction and wear of polymers against glass. The temperature rise is much smaller in this case compared to the steel system mentioned above. Preliminary results suggest that the temperature rise may be 20 to 30 C for a 2 mm diameter pin at 20 Newton load and a sliding speed of one meter per minute. The transparent disk in this case is CaF₂ to obtain adequate infrared transmission to measure the surface temperature. The friction and wear behavior observed by the BAM study have been repeated and the surface temperature data is being taken at this time. The collection of the temperature data will continue through the Summer of 1986 and, following discussions with the BAM researchers in September, a publication is expected.

A new study in cooperation with the BAM researchers has also been started. That is the measurement of the temperature rise in a fretting contact. They have been studying the fretting wear of ceramics against ceramics under load and oscillating speeds that we can duplicate. In the case of our studies we are loading a steel or ceramic ball against a sapphire plate and oscillating the plate while viewing the contact through the sapphire plate. Preliminary experiments indicate that measurable temperature rises can be observed. This work should prove to be quite useful. In general it is assumed that local

temperature rises do not occur in fretting wear. These experiments should be able to determine the extent to which this assumption is valid.

I Ib. Additional Use of Infrared System

The scanning infrared system used in this program was a major capital equipment instrument purchased on this grant. It should be of interest to NSF to know that this equipment is also being on two research projects of doctoral students; both in the school of Mechanical Engineering and one of which is in the Tribology laboratory.

The first is a doctoral student under the direction of Dr. Black who is studying the heat transfer from and temperature distribution on an integrated electronic circuit on a chip. The second is a class special project done by a doctoral student under my direction, Scot Bair. In a class taught by Dr. D. McDowell (a current NSF PYI) the question arose as to whether the material temperature rises at the tip of a propagating crack in steel and, if so, can it be measured. Scot utilized the infrared camera and was able to obtain images of the crack tip temperature rise for a crack propagating in steel. He also was able to measure the crack tip velocity to be about 25 meters per second. Although it is clear that the plastic zone dimension is smaller than the instantaneous field of view of the camera, the measurement suggests that the temperature rise is at least 90 C and may be 300 C or more. This research may be continued because of its obvious relevance to crack formation processes in tribological phenomena. The microscopic optics on the infrared camera purchased for the tribological studies has proven to be useful for both of these studies.

In summary several interesting and fruitful studies are underway and are expected to lead to publications during the next year.

III. Funds Estimated to be Remaining at End of Year.

This request is for the third year of funding to begin in mid-September. It is estimated that the funds remaining at that time will be less than \$1000.

Current and Pending Research Support

Ward O. Winer
Principal Investigator

(all research performed at Georgia Institute of Technology)

IA. Current support (in addition to current support on this grant at 4 man months per year).

- a. Martin Marietta Company-DOE-ORNL
"Development of a theory of Wear of Ceramics"
\$257,769
March 1983 to March 1987
Total of 5 man months commitment
- b. Hughes Aircraft Company (DARPA).
"High Temperature Solid Lubrication of Ceramics"
\$93,000
March 1, 1986 to March 1, 1987
Approximately one man month
- c. NSF
"Theoretical Studies of the Microscopic Mechanisms of Friction and Wear" Uzi Landman, P.I.
\$29,994
May 1, 1986 to October 31, 1987
No specific time commitment

IB. Proposals Pending

- a. NSF (this renewal proposal)
"Thermal Phenomena in Tribology"
\$299,966
July 1, 1984 to December 31, 1987
4 man months per year (or 33% time)
- b. NSF
"Modeling Boundary-Layer Tribology with the Langmuir-Blodgett Layer Probes" Lois Speaker, P.I.
\$305,975
Three years requested starting Sept. 1986
1.1 months per year
- c. DOE ORNL
"Wear-Resistant Ceramic Coatings for Diesel Engine Components" W.J. Lackey and R.F. Hochman co-PI
\$449,388
Submitted June 20, 1986, requesting 24 month period
Approximately three weeks total

- d. No other formal research proposals have been submitted at this time. However, consideration is being given to submitting an NSF ERC proposal in the next few months.
- II. S. Bair, Senior Research Engineer (research faculty associated with this proposal).
 - A. Current Support
 - a. Martin-Marietta - DOE - ORNL (IAa above)
12 months
 - b. Hughes Aircraft (IAb above)
Two months
 - B. Pending
 - a. NSF (this proposal IBa above)
 - b. Torrington Company
"Dynamics of Needle Bearings"
12 months
Three man-months
- III. n/a
- IV. This proposal is not being submitted to any other agency.

APPENDIX VII

NATIONAL SCIENCE FOUNDATION Washington, D.C. 20550		FINAL PROJECT REPORT NSF FORM 98A			
PLEASE READ INSTRUCTIONS ON REVERSE BEFORE COMPLETING					
PART I—PROJECT IDENTIFICATION INFORMATION					
1. Institution and Address George W. Woodruff School of Mechanical Engineering Georgia Institute of Technology Atlanta, GA 30332-0405	2. NSF Program Tribology (MSME)	3. NSF Award Number MEA 8320502	5. Cumulative Award Amount \$334,863.00		
4. Award Period From 7/84 To 6/88					
6. Project Title Thermal Phenomena in Tribology					
PART II—SUMMARY OF COMPLETED PROJECT (FOR PUBLIC USE)					
<p>Surface thermal phenomena at real areas of sliding contacts were studied focusing on the role of increased temperatures in the wear and load capacity of tribo-elements. High local temperatures are associated with tribocontact failure which often limits advanced mechanical system development.</p> <p>Measurements of the magnitude and dynamics of friction generated temperatures at the real areas of contact were made through transparent surfaces. Counterfaces used were hard ceramics, hard metals and soft polymers. Harder surfaces yielded smaller areas with higher and more transient temperatures than the softer surfaces where temperatures were low and evenly distributed. Size, temperature, and duration distributions show for the hard surfaces the temperatures are concentrated in small areas (about 50 to 80 micrometers diameter), have short durations (typically from 10 microsec to 200 milliseconds) and can be high (500 to 1000 C on metals and in excess of 2000 C for ceramics) supporting the possibility of local flow as a wear mechanism in hard materials do to the combination of high temperatures and the concomitant local weakening of the material.</p> <p>Analytical studies conducted support the experimental observations. These studies included the analysis of transient temperatures, the effect of surface layers, and the effect of specimen geometry.</p> <p>The capabilities developed have been applied in programs funded by industry and governmental agencies furthering the understanding of frictionally generated surface temperatures and the role they play in triboengineering. This grant supported or partially supported three completed doctoral theses as well as one postdoc and 12 archival publications. A twenty minute video tape was produced demonstrating the nature of frictionally generated surface temperatures which has been shown to over 250 conference participants. Several copies have been made and distributed to industry, government labs and academic institutions.</p>					
PART III—TECHNICAL INFORMATION (FOR PROGRAM MANAGEMENT USES)					
ITEM (Check appropriate blocks)	NONE	ATTACHED	PREVIOUSLY FURNISHED	TO BE FURNISHED SEPARATELY TO PROGRAM	
				Check (✓)	Approx. Date
a. Abstracts of Theses		x			
b. Publication Citations		x			
c. Data on Scientific Collaborators					
d. Information on Inventions	x				
e. Technical Description of Project and Results		x			
f. Other (specify) N/A					
2. Principal Investigator/Project Director Name (Typed) Ward O. Winer		3. Principal Investigator/Project Director Signature		4. Date 12/30/88	

FINAL REPORT

Submitted to

NATIONAL SCIENCE FOUNDATION

GRANT NO. MEA-8320502

THERMAL PHENOMENA IN TRIBOLOGY

by

WARD O. WINER

December 1988

FINAL REPORT
December 1988

NSF Grant: MEA-8320502
Principal Investigator: Ward O. Winer
Regents' Professor
George W. Woodruff School of Mechanical Engineering
Georgia Institute of Technology
Atlanta, Georgia 30332

Title: Thermal Phenomena in Tribology

Objective: To develop a basic understanding of selected problems associated with the thermal phenomena in tribology. The primary focus being to study the nature of surface temperatures in sliding contacts and the role of surface temperatures in wear and load capacity limitations of tribocontacts. High local surface temperatures are associated with tribocontact failure which is often a limiting factor in advanced mechanical system development.

Accomplishments: The studies can be divided along the lines of analytical modelling and experimental studies of surface temperatures in sliding contacts.

Analytical Modelling: Three papers have been published in which the behavior of surface temperatures in sliding contacts was reported. The first modelled the surface temperature transient occurring at a circular spot where frictional energy is dissipated on a semi-infinite solid [1 & Fig. 1]. The predicted transient times and peak temperatures predicted were consistent with those observed in the experimental portion of this study. The transient times can be of the order of 10 microseconds with peak temperature rises reaching 1000°C or more in typical real areas of friction contact 50 to 100 micrometers in diameter. The second paper was concerned with the role of the ever present surface layers on surface temperatures in frictional contacts [2 & Fig. 2]. Operational regimes defined by

dimensionless variables were determined showing where surface films substantially influence surface temperatures. The dimensionless groups were made up of the thermal transport properties of the film and substrate, the film thickness, the contact size, and the sliding speed.

In a third paper variations in the geometry and the thermal boundary conditions pertinent to the classical flash temperature theory were studied [3 & Fig. 3]. First, the case of multiple surface heat sources is presented. The relative location of the sources is the critical factor in predicting the local temperatures at each contact. Second, the case of a short cylinder (or a disk) is analyzed. In addition to the lateral surface boundary conditions, convective cooling from the side faces is considered. Third, the case of a hollow cylinder is studied where, in addition to the outer boundary conditions, uniform internal heating (or cooling) is considered.

A third analytical effort was the stochastic modelling of the surface temperatures at the real areas of contact in unlubricated sliding contacts. This model builds on the transient asperity temperature analysis. The location and size of the real areas of contact are generated randomly within specified limits. The specified limits are that the spot must be within the apparent area of contact, must have a diameter within a range consistent with experimental observation, and the total area of spots must be equal to the applied load divided by the material hardness. A given spot remains as an active load support as long as the maximum surface temperature is less than some fraction of the melting point of the material in degrees Kelvin. The last requirement is based on the assumption that as the surface temperature increases, as a result of frictional heating, it will reach a value where the material will flow under the applied stress. Once the flow begins the load is shifted to a new location. This model qualitatively fits some of the observations of surface temperature

dynamics as viewed in infrared video recordings. This modelling effort was redirected when funds became available from the DOE/ECUT program to undertake a transient thermal stress analysis with temperature dependent properties which could be used as the failure criteria. This research which was supported by this NSF grant and the DOE program resulted in one Ph.D. Thesis (B. Y. Ting, ref. 10) and two papers (ref. 13-15). This portion of the research showed that thermal softening and flow can be a mechanism of wear in brittle materials, such as ceramics, under some tribological conditions. The observation of that type of wear had been observed in the experimental part of this research program.

Experimental Observations of Surface Temperatures: Observations of surface temperatures proceeded along three distinct paths. These first two were concerned with hard bodies sliding against hard bodies. The third effort is concerned with the surface temperatures of compliant polymers sliding against a hard surface and is part of the cooperative program with BAM in West Berlin.

The pin-on-disk experiment was nominally steady (e.g., applied load and sliding speed) yet the real area of contact was very dynamic. By varying the film exposure time when photographing the hot spots at the sliding interface, the instantaneous number of real areas of contact could be estimated and was found to be less than or equal to seven. The results of this work are an important adjunct to the oxidational wear modelling work of T.F.J. Quinn [4 & Fig. 4].

The video analysis of the hotspots occurring on the surface of a steel pin in dry sliding against a sapphire disk resulted in several interesting observations. Using computer coupled video frame analysis statistics of spot size, number, total spot area, duration, and spot movement could be obtained. Typical results show that the average spot size is between 50 and 80 micrometers in diameter and the spot may persist for up to 200 milli-

seconds or more in some cases. As a rule, larger spots persist for longer periods. The average number of hotspots per frame appears to increase with load while the average diameter does not. The dependence of number, size, and intensity of hot spots on tribological operating parameters requires further study. The ratio of hotspot area to apparent area ranged from a high of 0.01 to 0.0001. In the limited attempt undertaken to relate the hotspot area to the load and the material hardness, no obvious relationship was found except that the load divided by the hardness may be an upper limit on the hotspot area as might be expected. One additional interesting observation was that in a few cases the hotspot persisted for several seconds and its position could be followed with the video analyzer. In one case, the hotspot persisted for three seconds and moved in the direction of sliding at an average velocity of about 100 micrometers per second before it disappeared. The surface sliding velocity was 2 meters per second. Therefore, the hotspot moved at a velocity about 5000 times slower than the opposing surface.

The coincidence of industry-supported automotive cam tribology studies and these thermal phenomena studies afforded the opportunity to measure the surface temperatures of operating cam and lifter surfaces. This work showed that at peak lift for cam speeds up to 1500 rpm and bulk oil temperatures of 100°C cam temperatures were up to 300°C. Temperatures of this magnitude have significant implications with respect to lubricant oxidation, lubricant surface reactions and surface layer formations [5 & Fig. 5].

The third area of surface temperature measurement is that of a polymer (PTFE) sliding against CaF_2 . The program was in cooperation with H. Czichos at BAM in West Berlin. The West German group has conducted an extensive study of the tribological behavior of polymers sliding against glass. The conditions used are a sliding speed of 17 mm/s and a load of 20 N on a 2 mm diameter pin. Our part of the program was to measure the surface

temperatures of the PTFE during sliding. We duplicated IR video recordings made with the CaF_2 counterface. The CaF_2 single crystal was chosen for its high IR transmission and because the temperature rise anticipated is only a few degrees Celsius. Surface temperature and bulk temperature of the PTFE pin, as well as bulk temperature of the disk at the end of the experiment, are measured. At the conditions mentioned above, surface temperature is constant within one degree and about 5 to 7°C above the bulk pin temperature 3 mm below the surface. As sliding speed is increased, these surface temperatures increase. It could not be concluded from these observations that the polymer wear observed at these mild conditions was thermally driven.

The grant also permitted this laboratory to participate in the VAMAS international study on the development of wear standard testing procedures. In addition to normal cooperation as a participating laboratory in the round robin procedures, experiments were conducted to measure the surface temperatures during the standard experiments. These measurements were incorporated in the summary publication by Czichos (ref. 7).

Additional Use of Infrared System: The scanning infrared system used in this program was a major capital equipment instrument purchased on this grant. This equipment was also used on two research projects of doctoral students; both in the School of Mechanical Engineering, and one of which is in the Tribology Laboratory. The equipment continues to be a major asset of the laboratory.

The first was a doctoral student, Stephen Fook-Geow Heng, under the direction of Dr. Black who was studying the heat transfer from and temperature distribution on an integrated electronic circuit on a chip. The second was a class special project done by a doctoral student under my direction, Scott Bair [6 & Fig. 6]. In a class taught by Dr. D.

McDowell (a current NSF PYI), the question arose as to whether the material temperature rises at the tip of a propagating crack in steel and, if so, can it be measured. Scott utilized the infrared camera and was able to obtain images of the crack tip temperature rise for a crack propagating in steel. He also was able to measure the crack tip velocity to be about 25 meters per second. Although it is clear that the plastic zone dimension is smaller than the instantaneous field of view of the camera, the measurement suggests that the temperature rise is at least 90 C and may be 300 C or more. This research may be continued because of its obvious relevance to crack formation processes in tribological phenomena.

Continued Studies: The capabilities, both experimental and analytical, for studying thermal phenomena in tribology developed under this NSF grant have established a firm basis for further research and development in the area. They have been a major reason for attracting additional governmental and industrial research funds to this laboratory.

References: (reprint copies attached)

1. Gecim, B. and W. O. Winer, "Transient Temperatures in the Vicinity of an Asperity Contact," Trans. ASME, Journal of Tribology, 107, No. 3, pp. 333-342, 1985.
2. Gecim, B. and W. O. Winer, "Effect of a Surface Film on the Surface Temperatures of a Rotating Cylinder," Trans. ASME, Journal of Tribology, 108, No. 1, pp. 92-97, 1986.
3. Gecim, B. and W. O. Winer, "Steady State Temperatures in a Rotating Cylinder - Some Variations on Geometry and Thermal Boundary Condition," Trans. ASME Journal of Tribology, 108, No. 3, pp. 446-454, 1986.
4. Quinn, T.F.J. and W. O. Winer, "An Experimental Study of the 'hot-spots' Occurring During the Oxidational Wear of Tool Steel on Sapphire," Trans. ASME, Journal of Tribology, 109, (1987), pp. 315-320.

5. Bair, S., J. Griffioen, and W. O. Winer, "The Tribological Behavior of an Automotive Cam and Flat Lifter System," Trans. ASME, Journal of Tribology, **108**, No. 3, pp. 478-486, 1986.
6. Bair, S., "Infrared Temperature Measurements in Dynamic Crack Propagation," submitted to the **Journal of Experimental Mechanics**.
7. Czichos, H., Becker, S., Lexow, J., ""Multilaboratory Tribo-Testing: Results from the Versailles Advanced Materials and Standards Programme on Wear Test Methods," Wear, **114**, pp. 109-130, 1987.

Doctoral Theses supported or partially supported by this grant (copies of abstracts attached).

8. B. Gecim, "Temperature Prediction in Mechanical Components, An Analytical Approach," March, 1984. (This thesis was completed just before the grant started. Gecim was employed as a postdoc on the grant for about nine months resulting in some of the published work cited.)
9. J. Griffioen, "Temperature Measurements in Tribo-Contacts by Means of Infrared Radiometry," June, 1985.
10. B.-Y. Ting, "A Thermomechanical Wear Theory," May, 1988.
11. S.F.G. Heng, "Experimental and Theoretical Thermal Analysis of Microelectronic Devices," June, 1988.

Additional papers published where work was supported or partially supported under this grant.

12. J. Griffioen and W. O. Winer, "Infrared Surface Temperature Measurements in a Sliding Ceramic-Ceramic Contact," Butterworths Publishing, Proceeding Leeds-Lyon Symposium 1985, Mechanisms, and Surface Distress, Dowson, Taylor, Godet, and Berthe, editors, pp. 238-245.
13. T.F.J. Quinn and W. O. Winer, "Thermal Aspects of Oxidational Wear," Thermomechanical Effects in Sliding Systems, F. E. Kennedy, Jr., ed., Elsevier-Sequoia, Wear **102**, 1985, pp. 67-80.
14. B. Gecim and W. O. Winer, "Thermal Conductivity of Lubricants at High Pressures," Trans. ASME, Journal of Tribology, Vol. **109**, July 1987, pp. 566-567.

15. B.-Y. Ting and W. O. Winer, "Friction-Induced Thermal Influences in Elastic Contact Between Spherical Asperities," ASME/STLE Tribology Conference, Baltimore, Oct. 1988 (to be published in **Transactions ASME, Journal of Tribology**).

NOTE:

Copies of all referenced papers and thesis abstracts were submitted to NSF with original of report. The papers are not attached here. If copies of the referenced papers are required, they can be obtained in the Tribology Lab of the School of Mechanical Engineering.

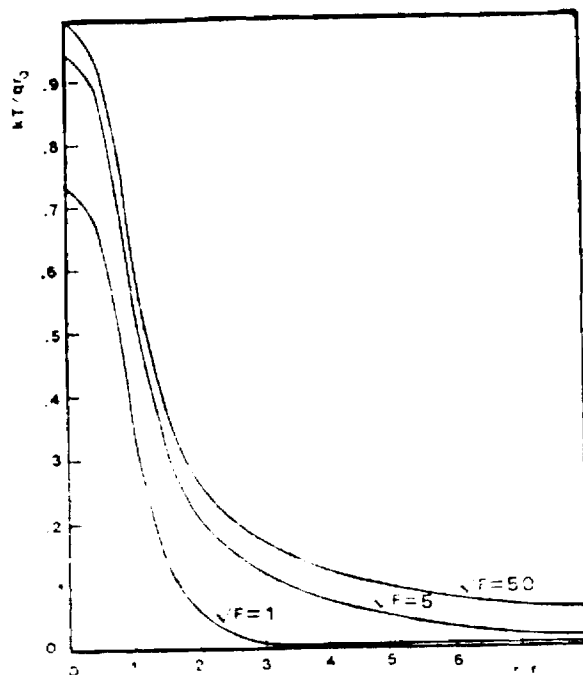


Fig. 1. Transient surface temperature versus radial position for three different Fourier numbers (r_0 is radius of spot where friction generated heat flux q is dissipated [Fig. 1, Ref. 1]).

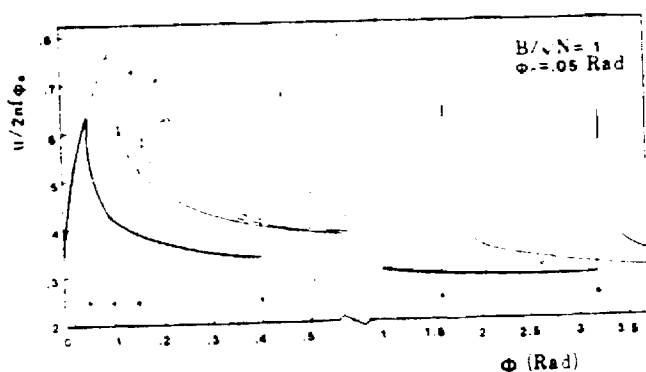


Fig. 3. The dimensionless surface temperature versus the angular location where the second heat source is placed at different positions as indicated by the arrows. The temperature distribution due to the first source along is shown by the thick solid line [Fig. 4, Ref. 3].

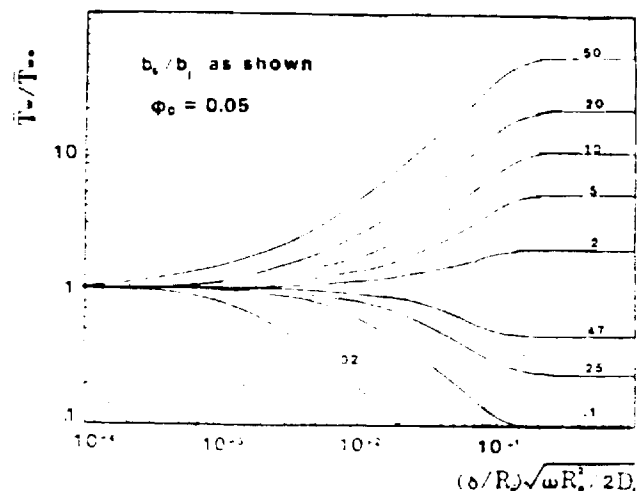


Fig. 2. The ratio of maximum surface temperature rise with the film to that without the film versus the product of dimensionless film thickness and square root of Peclet number [Fig. 4, Ref. 2].

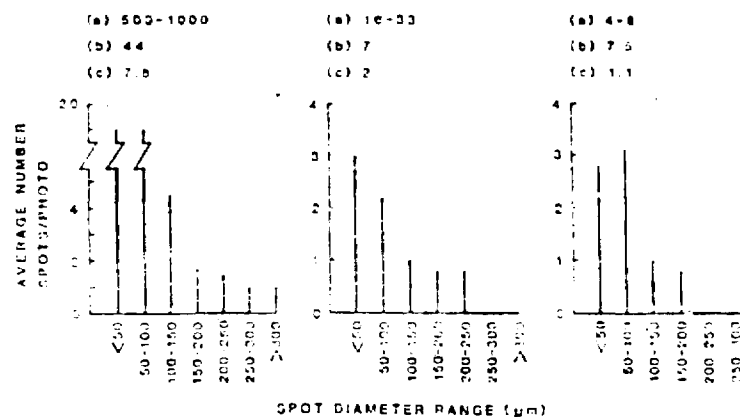


Fig. 4. Spot Size Diameter Distributions

- (a) Exposure Times (ms)
- (b) Average Number of Spots Per Photograph
- (c) Spot Area/Apparent Area of Contact ($\times 10^{-3}$) [Fig. 9, Ref. 4]

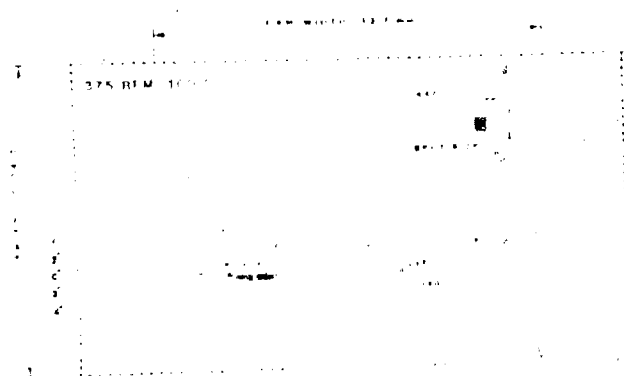


Fig. 16. Isotherms of the temperature distribution of Fig. 15. $N_{\text{car}} = 375 \text{ rpm}$, $T_{\text{bulk}} = 100^\circ\text{C}$.

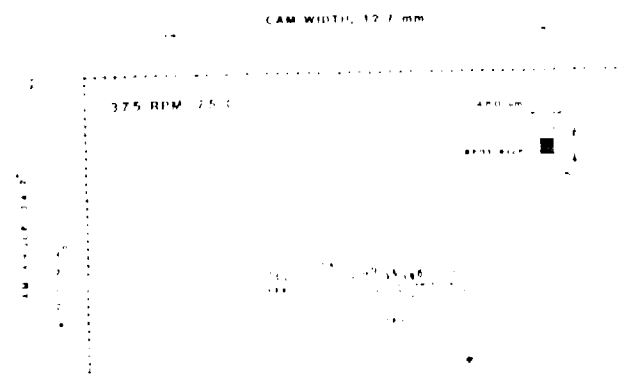
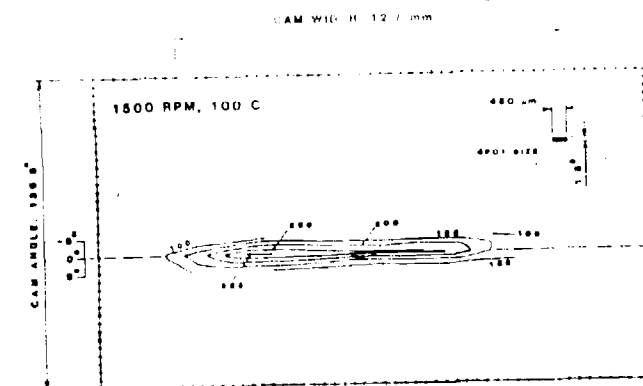
Fig. 17. Ice thickness, N_{ice} (mm), T_{bulk} ($^{\circ}\text{C}$).

Fig. 18 Isotherms, $N_{cam} = 1500$ rpm, $T_{bulk} = 100$ C

Fig. 5. Cam surface temperature at peak life for stated conditions [Figures 16-18, Ref. 5]

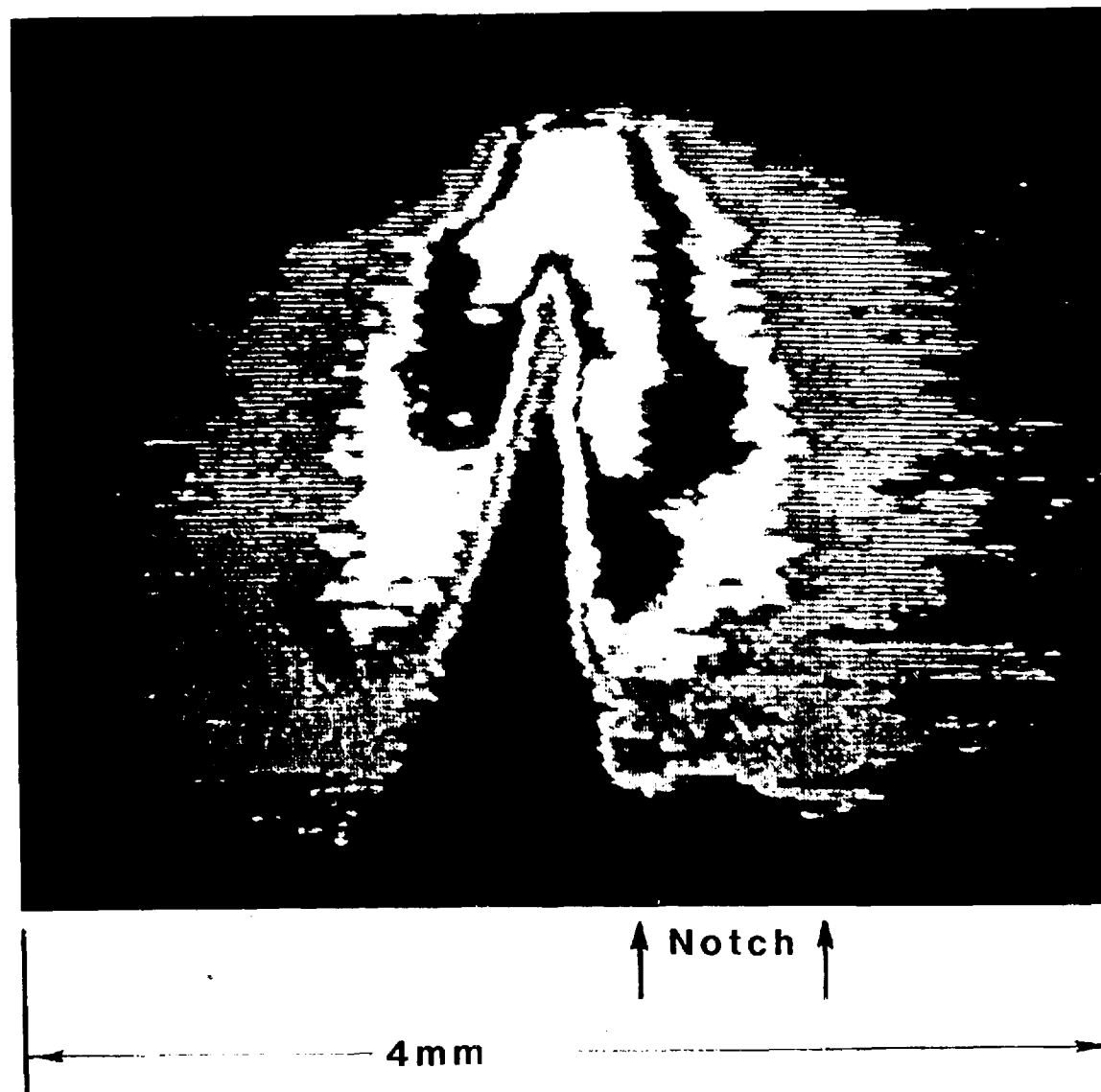


Fig. 6. Colorized thermogram of dynamically propagating crack in tool steel plate 0.4 mm thick. Original notch position noted. Scanning rate 4 kHz with an instantaneous field of view of 300 micrometers diameter [Ref. 6].